REVIEW OF FAA LCCA METHODOLOGY

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ABSTRACT

This paper addresses the findings, conclusions and recommendations drawn from a detailed review of the LCCA procedures presently followed by the FAA for pavement alternative development and selection. The review considered key aspects of both the pavement type design and selection as well as economic issues associated with alternative development. Key components, analysis tools and software, methods, and procedures were included in the review. Examples of why recommended techniques should be implemented are also provided.

INTRODUCTION

Life cycle cost analysis (LCCA) is described as “an economic analysis technique that allows comparison of investment alternatives having different cost streams” [1]. This definition, as it has often been applied, primarily addresses an aspect of the decision-making process associated with initial selection among pavement alternatives. However, a fuller utilization of LCCA in engineering decision-making can be realized through a better understanding and more in-depth pursuit of LCCA within a generated performance cycle. An improved tool for financial management of funds invested for construction and maintenance of our nation’s infrastructure can be a step in this direction, particularly if it is linked to both reconstruction and maintenance costs over time as a key criterion for alternative selection. Ideally, the application of LCCA could be carried out in a context of an overall strategy that is comprehensive, sustainable, and cost effective.

There are certain aspects within the performance cycle, such as remaining life and life extension, etc. versus the desired life that deserve greater consideration than they presently receive due to the importance they each can potentially have on the selection of a most preferred or final alternative. So should the tools and performance projection models used to carry out LCCA be capable enough to make such determinations with the needed consistency and engineering to have applicability throughout the entire alternative selection process for a wide variety of traffic, climatic, and pavement structure combinations. Improved mechanistic modeling is a must in order to advance LCCA and its capability to serve as useful means to make timely decisions in maintaining the sustainability of a pavement structure. Any efforts to expand upon the use of historical projection of performance (such as is presently portrayed in PAVEAIR) to have sufficient sensitivity to insure that timely and comprehensive decisions are made regarding how and when maintenance activities critical to the continued sustainability of a pavement system will prove to be fruitless and should be abandoned. This paper presents the results from a study of the present Federal Aviation Administration (FAA) LCCA procedures that considered both the economic and pavement performance aspects; only the performance related are presented herein. Furthermore, most of the examples discussed herein are concrete pavement related, nonetheless the application and utility of LCCA as discussed pertains as well to asphalt concrete pavement structures realizing that such examples are evolving particularly in light of the technological gains that are being made in the monitoring, modeling, and predictions on pavement distress. It will be important to embrace these advancements and how they impact the employment and configuration of LCCA with respect to associated evaluation tools, databases, and design procedures.

LIFE CYCLE COST ANALYSIS FRAMEWORK

The basic framework for life cycle cost analysis is typically presented in a step-by-step procedure. Although, not elaborated here, such a procedure was developed in the 1981 FAA Engineering Manual [2] and this procedure was followed in the "Economic Analysis" presented as Appendix 1 of FAA Advisory Circular 150/5320-6D, Airport Pavement Design and Evaluation, first in Version 6D [3] and later in Version 6E [4].

The U.S. Federal Highway Administration developed a similar step-by-step procedure in its publication [5] that led to the RealCost LCCA computer program [6]. This FHWA research describes a step-by-step procedure and places special emphasis on developing:

1) A method of calculating excess user costs associated with highway pavement construction activities, both for the initial pavement construction and for major rehabilitation actions, such as pavement overlays, within the chosen analysis period, and

2) A method of using computer simulation techniques to develop probabilistic estimates of life cycle costs.

The AIRCOST computer program is explicitly designed to follow the design of the RealCost program. Each step is designed as a "stand-alone" LCCA component such that feasible pavement design strategies can be analyzed in life cycle cost calculations separately from the program. The initial pavement section and the method of repair and service lives and the future rehabilitation alternatives are calculated separately from the AIRCOST program using whatever process the user has for completing the step-by-step procedure. This feature makes the widespread use of the program possible, because the determination of feasible strategies is left to the method chosen by the user. This feature undoubtedly accounts for the widespread use of the RealCost program.

CRITIQUE OF AIRCOST FUNCTIONALITY/UTILITY

Functionality in this paper refers to the capabilities of AIRCOST and its supporting software packages to support some aspects of LCCA assessment as part of an overall decision making process, which is paramount to the successful deployment of a pavement alternative development procedure. Functionality also includes the capability to facilitate comparisons among alternative or competing pavement sections or treatments as an integral part of making a decision with respect to the most desirable alternative. In this sense, the tools that support LCCA (i.e. BAKFAA, PAVEAIR, COMFAA, FAARFIELD, and PROFAA) are key components in the process of arriving at the optimal choice.

CONDITION ASSESSMENT

Presently, as far as obtaining an average pavement condition index, the pavement condition index (PCI) parameter , is for the most part a well configured index for pavement condition assessment (a part from a few exceptions) related to the weighting dictated by the shape of selected deduct curves. It includes and has sensitivity to a wide range of distress types for both asphalt and concrete pavement types that affect performance and the need for maintenance and repair. However, LCCA and alternative development selection should be sensitive to whether the distress type is structural or functional in nature which unfortunately is not explicitly represented in the PCI determination.

It is advantageous that the condition of a pavement segment be assessed according to its functional and structural capacity towards distinguishing the most appropriate form of maintenance, repair, and rehabilitation (MRR) technique. The assessment instrument, such as the PCI parameter, is often based on utility theory. In a broader sense, utility theory can be used to synthesize, digitize, and account for a variety of factors that play a role in decision making processes. In a previous FHWA study, Ledbetter et al. [7] developed an approach for the selection of pavement rehabilitation and treatments for asphalt and concrete pavements using utility theory to account for factors associated with cost, performance, safety, and energy usage. Utility theory facilitates a way to compare dissimilar things on the same scale (i.e., apples, oranges, and bananas) based on their:

- Value - the worth attached to an object or a service.
- Utility - the capability of a practice or an approach to satisfy a particular need or provide a desirable result.

With this in mind, utility based indices, such as in the PCI, can be established for a wide range of distress types:

- Structural Condition (SC)
  - Cracking (HMA, JRCP, and JPCP),
  - Existing patch density, and
  - Punchouts (CRCP)
- Functional Condition (FC)
  - Profile (P) and
  - Frictional resistance
- Profile (P)
  - Faulting (JRCP and JPCP)
  - Ride quality,
  - Existing spall density, and
  - Rutting (HMA).
- Overall Pavement Condition (OC)
  - Structural, and
  - Functional.

Utility theory relates expert opinion in the form of a rating to a physical phenomenon or evidence of physical changes such as the development of cracking in concrete pavement. It is made up of different features or attributes. For instance, the structural condition of a pavement section is a function of individual distress types, whereas the functional condition of a pavement section is a function of factors or attributes such as ride, friction, or other non-structural aspects. An overall condition utility of a given pavement section would be a weighted sum of the structural and functional conditions which would be an additional feature beyond what is done presently in the PCI determination. These weighted-utilities have an effect upon which LCCA alternatives should be selected since it is expected to dictate the life-cycle assessment behind any optimized maintenance, repair, or rehabilitation (MRR) strategy.

These weights can and often are user-defined which would allow a certain amount of flexibility in meeting established selection criteria. As it is done in the PCI computation, each component of pavement condition is assigned a utility (typically represented by a value between 0 and 10) determined in accordance with an assigned utility curve. The utility curve concept provides a means to characterize, for instance, pavement distress types such as the level of cracking distress. Such a relationship is typically established by the opinions of experienced pavement engineers much as was done in the development of the deduct curves in the PCI method and related to performance as a function of the distress types that affect performance. Repair of the cracked slabs would increase the utility of the pavement system with respect to cracking. This in turn would change the structural rating of the pavement at any traffic level since the cracking distress rating is included in the structural rating.

PROJECTION OF SERVICE LIFE

The PAVEAIR software is presently configured to project performance as a function of historical condition trends over a given period of time. Essentially, given the amount and quantity of data, a best fit regression curve is fitted to the field data to establish the trend line. This trend line projected to a critical threshold condition determines the pavement age or time that rehabilitation would be planned. There are, however, clear deficiencies to this approach:

1) The projections are limited to like pavement structures, climatic conditions, material properties, and traffic load distributions;

2) The projections are unable to distinguish between distress types or delineate the confounding effects of one upon the other;

3) The projections may not be capable to distinguish the effects of either previously or specific forms of rehabilitation, overlay types, or multiple alternatives;

4) Although the regression analysis associated with this approach does lend itself to an estimation of performance variance with respect to timing, it provides little or no indication with respect to distress density.

In order to incorporate an index with the prerequisite sensitivity to the variety of distress and performance factors associated with a given pavement condition, an assessment index or utility values would need to be established for each particular aspect of the pavement condition. It would also be useful to have some versatility built into how the amount that each distress type is weighted allowing it to be a function of the type of repair strategy to be applied.

For decision making related to alternative selection, an index sensitive to all the factors associated with the overall condition of the pavement is needed for the projection of pavement service life (as depicted in Figure 1) as well as being comprised of a weighted sum of the structural and functional ratings. Two useful factors associated with pavement condition shown in the figure are remaining life (RL – without further repair) life extension (LE). RL is a before-treatment condition assessment that represents the user's satisfaction that the pavement section's service level will be maintained for a certain projected time. LE is an after-treatment assessment that represents the user's satisfaction that the treated pavement section's service level will be maintained for a certain projected time following repair.

The determination of both remaining life and life extension should be based largely on the structural characteristics of the existing pavement system and the results of the pavement evaluation process. Furthermore, they are made using the type of distresses and their effect on performance where the pavement evaluation data is the foundation of the estimate of the expected remaining life in a given pavement structure. In addition, life extension also needs to be estimated based on the improvements afforded by the selected pavement treatment. It is evident that pavement life depends on the stiffness of the pavement system, and the degree that repairs restore the stiffness of the pavement system. This effect is critical when considering the impact, for instance, of full-depth repairs made with portland cement concrete versus asphalt concrete on the projection of service life. This determination is important from the standpoint that the projection of service life is an essential part of the life-cycle cost analysis which is depicted by the different types of pavement condition. Based on the projection of the various distress types (depending on the type of pavement involved), the pavement condition ratings can be projected over time relative to traffic level, as shown in Figure 1 (dashed lines).

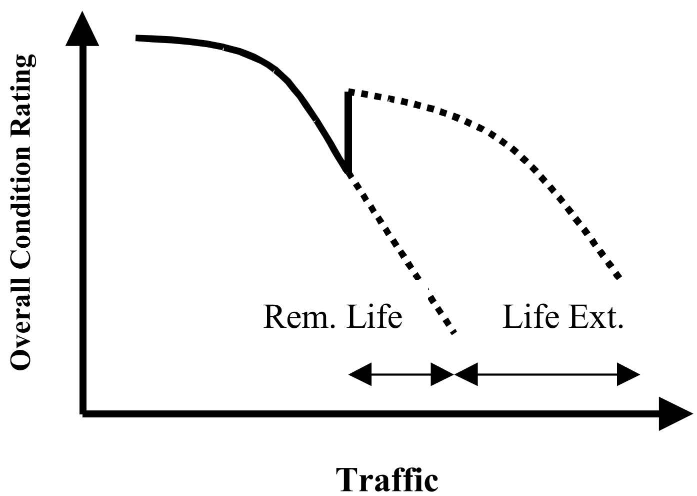

Figure 1. Depiction of Condition Rating Projections [8, 9, 14].

ALTERNATIVE DEVELOPMENT AND SELECTION

The basic idea behind the use of utility theory in LCCA related decision making for pavement design and MRR activities is that choices are made based on a broad range of factors that include cost, sustainability, and constructability as well as pavement condition. In other words, if there is a set of prerequisite preferences associated with the end results of a combination of future MRR treatments, then the best combination can be chosen on the basis of maximizing a variety of objectives (such as life extension, overall pavement condition, or cost). Furthermore, such preferences can be rated in terms of their utility (typically on a scale from 0 to 1) as well as their variances in terms of their ability to satisfy a decision maker's desires or criteria. As previously noted the PCI method is well configured to represent or assess the average pavement condition or utility (i.e. value); mainly because it includes and has sensitivity to a wide range of distress types for both asphalt and concrete pavement types that affect performance and the need for MRR. However, LCCA and alternative development and selection include more factors than those related to pavement distress and condition [8, 9].

With that said, a basic approach to identifying possible rehabilitation strategies is to package rehabilitation treatments at least initially, based on pavement condition, traffic, climate, and rehabilitation similarities and objectives to address key pavement deficiencies. That is, rehabilitation strategies are defined to address key distresses for the entire project, rather than on a distress-by-distress basis. This approach offers the following advantages:

- The number of options that must be evaluated is greatly reduced, because engineering criteria are used to package a set of compatible treatments that satisfy the rehabilitation objectives for each rehabilitation alternative.

- Each rehabilitation alternative represents the best engineering solution for the given rehabilitation criteria.

- Rehabilitation alternatives typically will not include redundant or overlapping treatments; however, within the context of this approach, alternatives that include routine maintenance may involve overlapping treatments.

RECOMMENDATIONS AND FURTHER DEVELOPMENT OF THE AIRCOST SOFTWARE

The review of the LCCA procedures as it pertained to the use of AIRCOST and its affiliated computer-aided analysis tools in airfield pavement type and repair alternative selection resulted in a series of recommendations for improvement and/or enhancement subsequently elaborated.

Deployment of LCCA for pavement construction or rehabilitation projects is best accomplished if it is utilized within the context of a broader set of considerations configured inside the framework of a decision making process leading to the most preferred alternative. In this manner, the development and use of LCCA software and tools is effectively configured within a network or project-level pavement management system as well as the design process. The databases relative to these systems potentially encompass the effects of several factors that reflect the condition of a pavement while the level of pavement distress manifested is useful to identify pavement repair treatments. At the project level, flight operations and construction management factors are often important in this decision process. The *pavement-related* (pavement condition, initial cost, repair type) aspects of MRR treatment selection are generally well developed, and even though the analysis of these aspects as well as the consideration of *nonpavement-related* (user delay and cost, future impacts, contractor availability, or other life cycle considerations) aspects of strategy selection are not as well developed. Nonetheless, the *nonpavement-related* aspects of an MRR strategy have perhaps the greatest impact in terms of non-agency considerations.

To facilitate the decision making process (DMP) within PAVEAIR relative to pavement rehabilitation, an approach is suggested that comprehensively considers both the *pavement-* and *nonpavement-related* aspects of an MRR strategy development. A DMP of this nature should lead to the most appropriate strategy for MRR of pavement chosen from a number of possible alternatives systematically considering all relevant factors. Within the framework of this discussion other issues relative to the reconfiguration of PCI to differentiate functional and structural distress, development of specific distress models for performance projection, use of

PAVEAIR as a calibration management tool rather than a performance projection tool given the consideration of variance and climatic effects in performance modeling.

ALTERNATIVE DEVELOPMENT AND SELECTION

Alternative development and selection involves a line of critical thinking to draw logically occurring relationships between different MRR pavement treatment types and the key decision factors in terms of design life, current pavement condition, and other factors that influence the treatment type performance. The decision to use any one or a combination of repair treatments depends on how well established criteria for feasibility, acceptability, and suitability (FAS) are met for rehabilitation. In fact, setting this type of framework within PAVEAIR could be a way to automate and categorize sets of rehabilitation actions or treatments from which the user could make choices that work to insure the success of the rehabilitation scheme.

The DMP would be configured to optimize the selection of a range of pavement treatments from maintenance to reconstruction based on a range of DMP factors encompassed within pre-established feasible, acceptable, and suitable (FAS) criterion. The following are factors that could be included in key FAS criteria [8, 9, 10]:

- Design life (length of the analysis period).
- Existing pavement condition (structure and functional).
- Air-side operations.
- Climate and drainage condition.
- Constructability (construction time and cost including life-cycle and user costs).
- Expected performance life (life extension).

Consideration of these factors and others allows an MRR strategy to be composed of one or a combination of individual treatments (relevant to a given pavement type and distress type) and the particulars affecting the use of each treatment. For example, a MRR strategy identified for a section of a continuously reinforced concrete (CRC) pavement might include two repair treatments such as diamond grinding and a HMA overlay. Each of these MRR treatments has different applicability that affects pavement performance and may have different impacts in terms of airfield traffic/operational delays or contractor skill level. These factors would be considered within the overall DMP as to the choice of MRR treatment. Consequently, since the effect of these treatment types are multiple in nature, they need to be individually weighted as to their effect on the choice of an MRR strategy.

DECISION FLOWCHART

A flowchart illustrating the basic structure of the MRR strategy selection DMP, shown in Figure 2, indicates the primary tasks involved and lays out the foundation for an automated alternative selection process. These tasks intermesh with current practices but use key information while guiding the user through a DMP leading to an optimized repair strategy.

As illustrated, four main tasks are involved in the decision process. Phase 1 is *Collect Project Data*. Here, the user provides general information about the project relative to its identification and general design features and other facts that define the overall analysis that lend consistency to the criteria involved in the DMP. Phase 2, *Conduct Pavement Evaluation,* involves assessment of the pavement condition based on field surveys and field laboratory tests from the pavement sections in question. The main objective of this phase is to obtain sufficient pavement condition data to ascertain the cause(s) of pavement deterioration.

In Phase 3, *Develop Suitable Strategies,* the decision flow relates to ultimately determining suitable treatment combinations. Based on the results of the field surveys and laboratory tests, the causes of pavement distresses are determined and used to formulate feasible treatment combinations. Several feasible treatment combinations result from this process, and at this stage, are reviewed with respect to their acceptability to perform at a prescribed level given the application and existing pavement condition. An example of acceptability criteria for concrete pavement structures is outlined in Table 1. This table outlines 4 different types of strategies listed

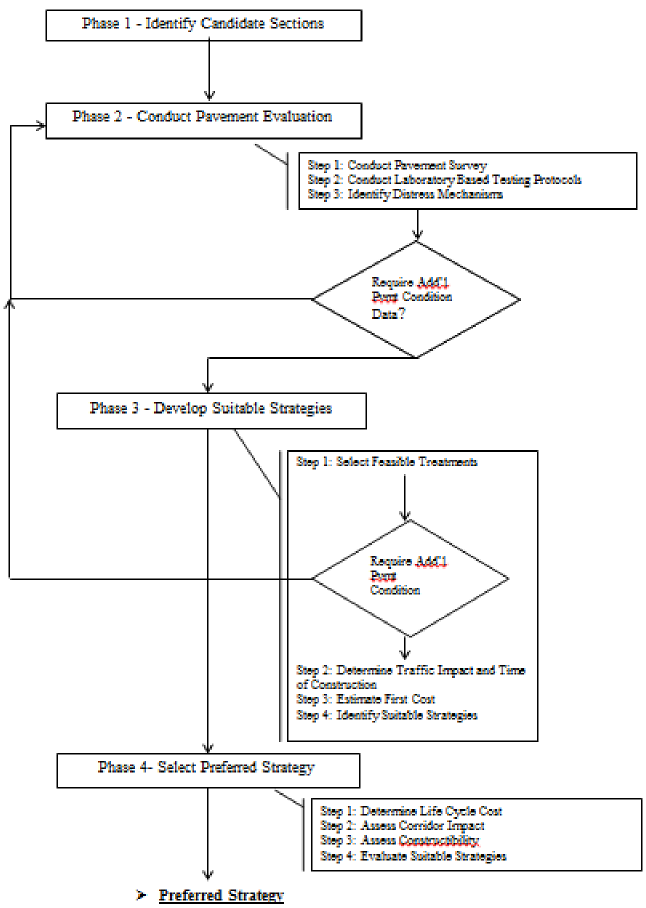

Figure 2. DMP for Selecting MRR Strategies [8, 9, 11, 12].

in sequential order that could be considered depending upon the acceptance criteria but the first one addresses routine maintenance. The acceptance criteria for each type of strategy are related to some aspects of the structural or functional condition of a pavement system. The strategy selected is the first one where the condition limits are met.

In Phase 4, *Select Preferred Strategy,* key *nonpavement-related* issues are addressed in detail. A detailed analysis of life-cycle cost is conducted along with an analysis of non-agency costs for each MRR strategy, plus constructability and corridor impact analysis and assessment. Using these results, the optimal strategy is selected for detailed design and construction. Within PAVEAIR, the preferred alternative would be based on results from the LCCA in addition to other factors related to the final pavement condition as a result of the repair as well as construction and the sustainability issues related to the effect of the repair.

Table 1.
Treatment Combination/Strategy Selection Acceptability Criteria [8, 9].

Strategy Type	Decision Attribute	Weighted Attribute Component	Suggested Decision Criteria Limits (% of scaled value)
To Conduct Routine Maintenance *(Cost-driven solution)*	Structural Condition (SC)	Distress Type Distress Level Remaining Life (RL)	If SC Rating > 50% If RL Rating > 50%
	Functional Condition (FC)	Ride Profile Skid Resistance Tire Noise[a]	If FC Rating > 50%
To Conduct Repair (CPR) *(Engineering-driven solution)*	Structural Condition (SC)	Distress Type Distress Level Remaining Life	If SC Rating < 50% If RL Rating < 70%
	Functional Condition (FC)	Ride Profile Skid Resistance Tire Noise	If FC Rating < 50%
To Use Overlay	Suitability for Overlay	Life Extension (LE)[a]	LE Rating > 80% (BCOL) LE Rating > 50% (UBOL) LE Rating > 70% (CRC) LE Rating > 50% (ACOL)
To Reconstruct	Suitability for Reconstruction	T/W, R/W Geometry (OC)[+] Remaining Life (RL)[a] Life Extension (LE)	OC Rating < 50% RL Rating < 50% LE Rating < 50%

[a]Ratings are user-defined.

DEVELOPMENT OF SPECIFIC DISTRESS MODELS FOR PERFORMANCE

To achieve breadth and depth in distress representation and the perquisite relevancy in the LCCA, it is important to develop or adopt models to represent the range of distress mechanisms key to performance projection upon which the LCCA is based. Presently, PAVEAIR projects performance based on PCI trends; SCI, which is similar to PCI in how it represents the condition of a pavement, strictly speaking only represents (in conjunction with FAARFIELD) the effects of fatigue cracking in design since that is the only distress mechanism represented in the CDF parameter for rigid pavement, for instance. Simply stated, there is an unexplained disconnect between PCI and SCI that could be avoided within the LCCA decision framework by dropping the use of PCI in the cracking model that unnecessarily complicates the projection of distress on a broader scale. With respect to the effect of other types of distress types, as well as fatigue cracking, the parameter used to represent pavement condition should be a function of the results of the distress model rather than the other way around.

Every pavement type can be associated with a characteristic set of distress types that should be represented in an LCCA process in order to account for the effects of pavement deterioration and use on performance. The FAARFIELD software would perhaps be better utilized if a broader range of responses were drawn from it. Certainly three-dimensional FEM analysis has utility beyond the assessment of bending stress that should be capable of addressing a wider range of responses and distress modes. Complete design analysis involves a multitude of distress modes that should define a full-range of failure conditions that can occur with a given pavement type. In order for the results of LCCA to be relevant, key distress types need to be modeled and locally calibrated to field data to better account for difficult-to-define construction and climatic factors on performance. Performance model development is about the understanding of the nature and characteristics of a particular mode of failure and involves:

- Defining basic performance trends and variances with respect to traffic that are understood, known, and definable based on field observation and experience,

- The inclusion of key material properties and pavement response parameters and their variances relevant to the distress type or mode of failure, and

- A statistically-consistent and rigorous configuration that is amiable to a calibration using either laboratory or field data.

Development of performance models are typically built around an essential premise of tracking known trends either with traffic or accumulated damage. These trends are also associated with accumulated statistical distributions that have established or defined mathematical relationships. These accumulative relationships are either Weibull or hyperbolic in nature and are relatively easily transformed and fit to field or lab data. This is an important feature in terms of calibration a topic subsequently discussed.

Another important aspect of model development would be the inclusion of key material properties that influence or are involved is the distress mechanism. The most common type of material properties are strength related determinable with standard test methods under laboratory conditions. A typical model for mid-slab fatigue damage (FD) used in the AASHTO ME pavement design software ($\overline{FD} = \sum \frac{\overline{N}}{N_f}$ where N is the accumulated load applications and N_f is the allowable number of accumulated loads) cracking in concrete pavement, for instance, is:

$$\overline{\%C} = \frac{100}{1 + C_4 \overline{FD}^{C_5}} \tag{1}$$

with the calibration coefficients C_4 and C_5 and representing the form shown in Figure 3. Since equation (1) provides a prediction of the average cracking, the average fatigue damage for the project is used in the model. The average damage is calculated and accumulated over time and traffic as a parameter that represents a relative index of load associated damage within the pavement structure. As the computed "damage" increases (e.g., as noted in Figure 3), more and more slabs are expected to develop cracking within a given project. The incremental damage as accumulated month by month can be correlated to the physical pavement distress of transverse mid-slab cracking through calibration of the calculated damage to the observable distresses. Such a correlation can be developed by plotting a graph of the ( ) pairs ideally from a number of pavements that have similar climatic characteristics to find the two coefficients by regression analysis of the available data points. The cracking model is mathematically manipulated so that it relates, for instance, the percent slabs cracked in jointed concrete to the number of load applications shown in Figure 4. Rearranging equation (1) in terms of load applications yields a convenient form for carrying out the calibration analysis:

$$\overline{\%C} = \left[1 + C_4 \overline{N}^{C_5} N_{f_c}^{-C_5}\right]^{-1} \tag{2}$$

The N_f parameter has a subscript 'c' associated since that can be determined from the field data as presented in Figure 4 by associating it with the maximum allowable amount of fatigue cracking. For calibration purposes, this is one of the best means of assessing this parameter for a couple of reasons pointed out later but this approach allows the cracking model to be linearized ($y = b + mx$) to easily fit the field data to determine the only 2 unknowns (C_4 and C_5) in the following fashion:

$$\begin{gathered}\left[\frac{1}{\overline{\%C}} - 1\right] N_{f_c}^{C_5} = C_4 \overline{N}^{C_5};\ Ln\left\{\left[\frac{1}{\overline{\%C}} - 1\right]\right\} = Ln(C_4) - C_5 Ln\{N_{f_c}\} + C_5\{Ln(\overline{N})\} \\ y = b + mx;\ y = Ln\left\{\left[\frac{1}{\overline{\%C}} - 1\right]\right\};\ x = Ln(N);\ m = C_5;\ b = Ln(C_4) - mLn\{N_{f_c}\};\ C_4 = e^{b + mLn\{N_{f_c}\}}\end{gathered} \tag{3}$$

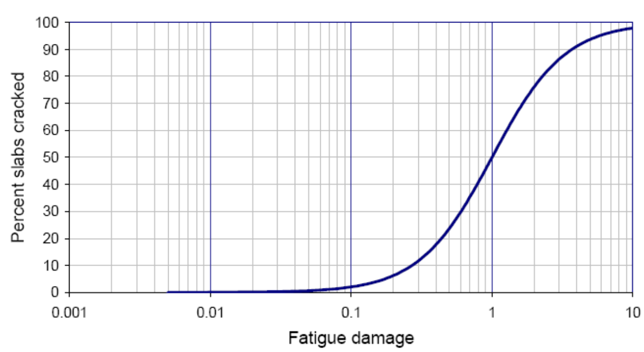

Figure 3. Form of the Relationship between % Cracking and Fatigue Damage.

The regression process accomplishes two objectives:

- Yields the average values of the calibration coefficients, and their
- Variance

which plays an important role in determining the variance of cracking and the related LCCA. As an additional note in this regard, in the assumed curve form shown in Figure 4, the mean-squared error is assumed to be the standard deviation of the cracking (i.e. the probability density function (PDF) - item (a) shown in Figure 4) or the standard deviation of the traffic, $\overline{N}$ (PDF - item (b) also shown in Figure 4) at a set value of $\overline{C}$; depending upon the nature of the dataset, $\overline{N}$ may or may not be the standard deviation of the number of applications at that level of cracking.

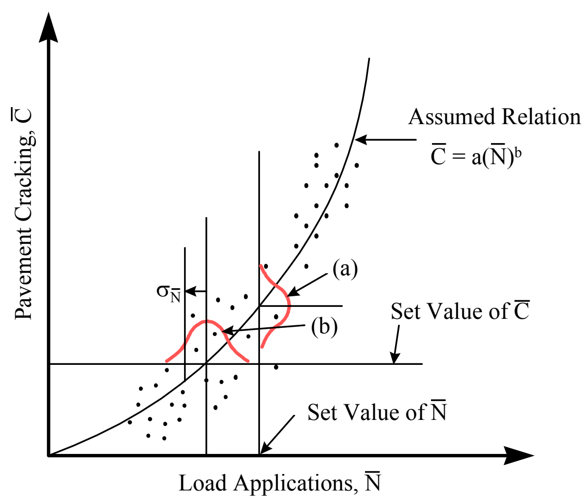

Figure 4. Pavement Cracking versus the Number of Load Applications (13).

Nonetheless, equation (1) is an accumulative form that has a PDF (*p(FD)*) defined by differentiating it with respect to *FD* as:

$$p(FD) = -A\frac{\alpha\beta(FD)^{\beta-1}}{1+\alpha(FD)^{\beta}} \tag{4}$$

where the estimated mean (*E(FD)*) of the distribution can be found from:

$$E(FD) = \int_{-\infty}^{+\infty} FD_i d\ p(FD) dFD \tag{5}$$

and the estimated variance (*VAR(FD)*) from:

$$VAR(FD) = \int_{-\infty}^{+\infty} (FD_i - \mu_{FD}) p(FD) dFD \tag{6}$$

It's in this manner, that the calibration coefficients determined from the regression of the specific performance data will yield a calibration for both the mean of the performance trends as well as the variance of the performance. In other words, the calibration coefficients can be tied to the statistical distribution of the fatigue damage as it varies over time. These are somewhat subtle points that are nonetheless extremely important in defining and laying out a consistent and integrated approach to performance modeling and calibration for the purposes of supporting a probabilistic assessment of LCCA.

Using PAVEAIR to simply provide local performance data would be an important step to take to better support calibration efforts as a necessary and needed move towards improved projection of performance that is capable of accounting for the effects of variance that reflects unique aspects of the behavior of the pavement, its modes of failure, and how they interact to shape the performance of the pavement over its service life that would otherwise remain unaccounted for. The same types of inputs involved in the design process need to be addressed in the calibration process in terms of material properties, environmental effects, and pavement condition information. A complete LCCA process addresses a variety of distress types which include several performance models each requiring their set of locally defined data for calibration.

From the above paragraphs, it is clear to support a probabilistic and integrated approach to LCCA that a statistical analysis of available performance data be involved that is consistently tied to both a condition and structural analysis of the pavement section. The structural analysis will quantify the effects of mechanistic independent variables such as the pavement thickness, material strength, and traffic loading on primary structural responses such as stress and strain. The mathematical forms shown above for a relationship, for instance, between the occurrence of cracking and primary structural responses are used in the probabilistic analysis of service life is a direct feed into LCCA.

INTEGRATION OF AIRCOST AND FAARFIELD

The integration of AIRCOST and FAARFIELD can be done systematically and consistently within the framework of the overall DMP previously described and as depicted in Figure 5 with respect to the key FAA program components. The three components shown provide the tools to make performance life estimates needed to improve the capability of AIRCOST to utilize robust and realistic estimates of performance life. This arrangement along with the calibration of the different performance models (aided by the results from BAKFAA, COMFAA (not shown), and PAVEAIR) will achieve this result. In other words, the PAVEAIR program would provide the performance database in which to provide local calibration data for the life projection calculations associated with LCCA. Once properly configured and automated, the AIRCOST software will be able to provide LCCA for selected pavement alternatives that are considered over a wide range of distress types and factors affecting alternative selection. FAARFIELD should be capable of providing the needed pavement response parameter and that is used in the DMP at two distinct locations:

1. As part of decision criteria associated with alternative development (as part of AIRCOST), and

2. In the projection of pavement service life (also as part of AIRCOST).

Pavement response often consists of the following:

- Pavement deflection (δ),
- Pavement stress (σ), or
- Pavement strain (ε).

A key input however for AIRCOST (and PAVEAIR as well) is the projection of service life under existing conditions and with different alternative methods of repair. Life projection, as noted previously, is often a function of a given pavement response to either an applied load or climatic effect depending upon the type of pavement and the type of distress involved. The point is the DMP distinctly identifies where AIRCOST and FAARFIELD fit into the process and the roles that each fulfills in arriving at a preferred alternative.

As noted previously, the same distress types included in the LCCA also need to be included in the design process in order for life projection of the original pavement design alternatives to be consistent with life projection for alternative methods of repair. Presently, FAARFIELD is only employed to project fatigue cracking in design while PAVEAIR, although poorly conceived, is technically capable of considering most distress types (if not all) in the projection of PCI-defined life over time is nevertheless highly limited within the context of the existing pavement section. By using a modeling approach to life projection, the role that FAARFIELD could play would be significantly expanded since the employment of multiple distress types would require multiple response parameters. The projection of pavement life in terms of multiple distress mechanisms to yield a variety of distress densities which feeds directly into the LCCA and the calculation of PCI (or SCI) as a means to represent the effect of all distress densities at play over time. The representation of multiple pavement configurations and alternatives in pavement response and life extension computations would in part fit well within the capability of the FAARFIELD FEM code.

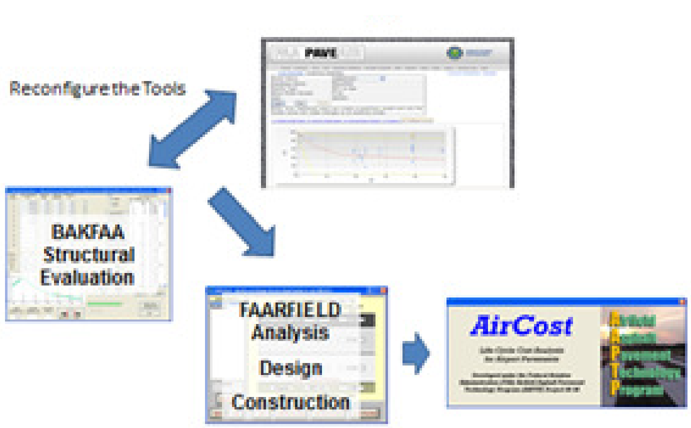

Figure 5. Key Components Related to the Integration of PAVEAIR [15].

CONCLUSIONS

Several conclusions were made as a result of the review of the FAA LCCA procedures some of which are listed below. In general, the conclusions range from improvement of the M-E modeling capability for design and performance analysis to the development of a systematic and methodical decision-making process to control the repair selection process.

1. The state of mechanistic modeling of pavement distress for asphalt and concrete pavement types as configured in the FAA present method of design and analysis is in great need of advancement to broaden/improve:

    a. The efficiency of FAARFIELD with respect to specific distress types and mechanisms, pavement responses, load configurations, load magnitude, and path wander.

    b. The range of responses and distress types, and

    c. The range of alternative pavement configurations and repairs it considers.

2. Although, not addressed in this paper, the effect of climate should to be incorporated in the assessment of performance both on a short term (during construction) and on a long term (i.e. its effect on pavement behavior) basis.

3. Although only briefly referred to, performance variance should to be rigorously incorporated into the assessment of life and other factors to be considered towards the determination of LCCA on a probabilistic basis.

4. PAVEAIR should be transformed and more closely integrated with BAKFAA to produce and manage a complete and detailed database in which to carry out performance model calibration and constrict historically based performance projection capability to no more than 5 years into the future. Performance database utility is greatly enhanced if it is configured with distress and related pavement structure data to support calibration efforts. Performance models will need to be configured for calibration if life projections are to be 40 years.

5. A consistent and structured pavement alternative and repair development process is non-existent and should to be established with respect to specific decision criteria and conditions for key stages of the selection process. Portions of the decision criteria should be based on PCI which should be:

    a. Used as an index of pavement condition as it may vary over time and traffic with distress density and type,

    b. Reconfigured in terms of not only a mean value but also its variance that is tied to the variance of specific distress type(s), and

    c. Subdivided into structural and functional distress types to better support alternative pavement repair development.

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